

# Field Trials of a NASA-Developed Mobile Satellite Terminal

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## ABSTRACT

Various field trials have been performed to validate and optimize the technologies developed by the Mobile Satellite Experiment (MSAT-X). For each of the field experiments performed, a brief description of the experiment is provided, followed by a summary of the experimental results. Emphasis is placed on the two full scale land-mobile and aeronautical-mobile experiments. Experiments planned for the near future are also presented.

## 1. INTRODUCTION

The MSAT-X Task is dedicated to developing system concepts and high-risk technologies to enable the introduction of commercial land-mobile satellite communications in the United States.

MSAT-X developments have centered around the efficient utilization of the scarce resources of bandwidth, power, and orbital slots. The proposed architecture is based upon one or more bent-pipe satellite transponders; spot beams for mobile coverage; vehicular tracking antennas; low data rate speech compression; and modulation techniques which are both power and bandwidth efficient, and robust to the impairments of the mobile channel.

In this dynamic and challenging environment, field trials are imperative to validate the critical technologies and the underlying system architecture. The field trials, collectively called the Pilot Field Experiments (PiFEx), have evolved from testing individual subsystems, to end-to-end system demonstration. Accordingly, the objectives have been to: 1) evaluate the actual performance of the subsystem elements in relation to expected performance (theoretical or simulated), 2) evaluate the end-to-end performance of the system, 3) obtain

data to support the enhancement of the system components and architecture, and 4) demonstrate system potential to end users and manufacturers.

To meet these objectives, a variety of field experiments have been formulated and conducted. In the following sections the ground terminal and test equipment are first described briefly. This is followed by a concise history of the PiFEx program and a more detailed description of the two full-scale aeronautical and land-mobile experiments. Experiments planned for the future are also described. Conclusions emerging from the field trials are then presented.

## 2. SYSTEM DESCRIPTION

Three distinct classes of equipment were used in the experiments: the MSAT-X terminal(s), a translator or satellite transponder, and the supporting test and data gathering equipment. For all experiments the terminals at both ends of the link were functionally similar and were basically copies of the MSAT-X mobile terminal. No formal network control center was required, although the required link set-up protocols were implemented in the terminals.

The major components of the mobile terminal [1] are the speech codec, the terminal processor, the modem, the transceiver, and the antenna. The speech codec provides good quality speech at 4800 bits per second (bps). The terminal processor acts as the heart of the mobile terminal, and implements all networking and control functions. The modem converts data from the terminal processor at 4800 bps into a baseband waveform, as well as demodulates a low IF from the receiver to provide 4800 bps data to the terminal processor. The transceiver up-converts the baseband waveforms from the modem to a suitable L-band transmit frequency. It also receives the signal at L-band, and down-converts the

signal to the IF required by the modem. The transceiver coherently demodulates and tracks a pilot signal and provides it to the antenna subsystem for tracking. It is also capable of using the recovered pilot as a reference for the down-conversion chain to the modem (this removes the one way Doppler from the received signal). The antennas developed for MSAT-X range from omni-directional drooping dipoles to mechanically and electronically steered arrays. Typically, the omnidirectional has been used for a reference pilot receiver (for propagation measurements) while the tracking antennas are used for data reception and transmission.

In addition to the basic communications terminal, enhancements for experimental purposes include a data acquisition system (DAS), an  $E_b/N_0$  measurement subsystem, an audio record/playback unit, and various pieces of test equipment. The DAS performs real time analysis and displays key data for the benefit of the experimenters in the field. The DAS also records more extensive information for post-experiment analysis, such as baseband received pilot (in-phase and quadrature channels for propagation measurements), antenna pointing parameters, etc. For the mobile terminal (versus fixed) enhancements to the terminal have included a Loran C (position determining) receiver, a flux-gate compass with digital outputs, a digital speedometer, and a video camera. All of the outputs from these additional data systems, except the video camera, are also recorded by the DAS.

For field test purposes, an L-band translator was developed to allow simulated satellite tests using an antenna range or large tower.

### 3. PIFEX

The Pilot Field Experiments have covered a range of activities: from simulated satellite experiments using a translator and a tower as a satellite simulator, to full scale satellite experiments. A summary of these experiments is presented in Table 1.

#### Tower Experiments

A series of tests were performed using a 1000 foot NOAA tower in Erie, Colorado. These included antenna acquisition and tracking (Tower 1 [2]) using the JPL mechanically steered antenna; antenna tests and half duplex data transmissions using the MSAT-X modulator and the JPL and TRE steerable antennas (Tower 2 [3]); and full scale system tests

(Tower 3 [4]). In Tower 3 full duplex speech and data transmissions were conducted using both the JPL and TRE antennas. Tower 1-3 served as a series of shakedown tests for the mobile terminal, and many operational obstacles and system deficiencies were identified and overcome. Indeed, further tests to be described below have shown that, in many respects, the tower set-up created an environment that was more severe than actual satellite environments.

#### Satellite 1a

The Satellite 1a experiment was the first of the PiFEX experiments using a real satellite, and was conducted in Santa Barbara, California during August of 1987 [5]. This experiment used a beacon from the MARISAT satellite to serve as a pilot signal for antenna tracking. The JPL mechanically steered antenna was used and a series of mobile tracking tests were run in the Santa Barbara area. This experiment was significant because it was the first time the antenna had tracked a true satellite, and in particular, with the very low elevation angle ( $13^\circ$ ) to the satellite. The experiment verified the JPL antenna's mechanical robustness and tracking capabilities in a very demanding configuration (the JPL antenna was designed for a  $20-60^\circ$  elevation range). In addition to verifying the antenna performance, numerous propagation results were obtained and analyzed.

#### MSAT-X/FAA/COMSAT/INMARSAT Experiment

The joint MSAT-X/FAA/COMSAT/INMARSAT experiment consisted of ground based experiments conducted during the first three weeks of January, 1989, and aeronautical experiments conducted during the last week of March 1989. The objectives of the experiments were to characterize the MSAT-X mobile terminal performance, for both the fixed ground and aeronautical-mobile satellite link environments. Link and equipment characterizations were performed by collecting both BER results at various signal to noise ratios (SNR) as well as evaluations of the speech link performance [6].

The experiment configuration is shown in Figure 1. The ground experiment consisted of a ground-to-ground full duplex communications link between the FAA Technical Center in Atlantic City, New Jersey, and the COMSAT ground station in Southbury, Connecticut, through the MARECS-B2 satellite. The aeronautical experiment was functionally similar to the ground segment. Experiments took place with

the aircraft stationary and with the aircraft following prescribed flight paths. In both parts of the experiment, the MSAT-X terminal was used except that passive dual helibowl antennas were used instead of the steerable antennas. Two antennas were used on the aircraft, one on each side of the fuselage attached to the inside of a passenger window. At the ground locations and during flight the elevation angle to the satellite was approximately  $23^{\circ}$ .

The measured ground based BER for the forward link (FAAT.BER) and the return link (CEST.BER) are shown in Figure 2. Plotted on the same graph are the curves for simulation (SIM.BER) and laboratory hardware tests (LAB.BER), both for an additive white Gaussian noise (AWGN) channel. The experimental curve is about 0.5 dB from the laboratory measured performance for the forward link and very close to the laboratory results for the return link. The primary sources of degradation in the forward link are the operation of an automatic level control circuit in the satellite, and noisy pilot tracking at the receiver. Ground based voice links were established to demonstrate the digital speech coder. Both conversations and standard speech tapes were recorded. The voice quality was considered to be very favorable.

Once the equipment was installed in the aircraft, ground calibrations were performed to establish a benchmark for the flight tests. These calibration tests were found to differ from the previous ground-to-ground performance results by about +0.1 dB in each link due to window aperture effects.

Following the calibrations, two flight tests were performed. The flight paths followed are detailed in Figure 3. During both flights, the aircraft was flown at an altitude between eight and nine thousand feet, with ground speed that ranged from 180 to 290 knots.

Along both paths of the first flight, heavy turbulence due to severe thunderstorms was encountered. The average performance in the forward link for both legs of the flight (ACT.329) and the return link for both legs (CEST.329) are shown in Figure 4. Also shown in this figure is the average forward (ACT.328) and return (CEST.328) link performance for the aircraft ground calibration. There is approximately a 0.8-1.0 dB degradation in link performance due to the aeronautical environment. This degradation comes from several factors, including the pitch and roll of the aircraft caused by the heavy turbulence, and the change in the received

Doppler (which varied on the northerly flight path from approximately 128 Hz at one end to 79 Hz at the other of the flight path).

The experiments conducted during the second flight consisted of data transmissions from the aircraft to the ground and speech demonstrations. At course changes the received Doppler changed rapidly and over a fairly wide range (e.g., +218 Hz to -223 Hz as shown in Figure 3). Residual Doppler on the order of  $\pm 100$  Hz remained after coarse compensation was performed using the transceivers. The BER results for the return link from the portion of the flight path from Charleston, South Carolina to the first major course change are shown in Figure 5 (CEST.RHS.331). For comparison, the return link performance of the ground based aircraft terminal is also shown (CEST.328). As can be seen, the performance is very close to the ground tests. The primary reason for this is that little turbulence was encountered on this portion of the flight.

During both flights, the full-duplex MSAT-X voice link was established often and used as the main, and, in fact, the only available direct voice link between the experimenters on the aircraft and in the CES. There was no perceptible difference in speech quality or intelligibility between in-flight and ground operations. In particular, the background jet noise had no significant effect on the communications.

In summary, while the link between the aircraft and the ground was more dynamic than expected, the operation of the MSAT-X mobile terminal was very close to theory/simulation and laboratory results.

### MSAT-X/AUSSAT Experiment

The joint MSAT-X/AUSSAT experiment was conducted in Australia from July 17th through August 2, 1989. The experiment tested for the first time, the MSAT-X technologies and equipment in a true land-mobile satellite environment. Speech and data communications were demonstrated and tests were performed to characterize, quantitatively and qualitatively, MSAT-X system performance. Extensive data was recorded for various system parameters, as well as for vehicle antenna validation and propagation studies. A secure voice experiment for the United States National Communications System (NCS) Agency was also performed.

The experiment configuration is shown in Figure 6. The land-mobile satellite link consisted of a fixed

hub station at AUSSAT Headquarters in Sydney, the Japanese Experimental Technologies Satellite (ETS-V), and JPL's MSAT-X van. The van and hub station contained the basic MSAT-X communications terminal and other test and data-acquisition equipment. Two steerable antennas were available for use on the van: the JPL mechanically steered antenna, and the electronically steered phased-array antenna developed for JPL by Teledyne Ryan Electronics (TRE). (See [1] and the references therein.)

Mobile tests were conducted along Highway 1 between Sydney and Brisbane. Elevation angles to the satellite ranged from  $51^{\circ}$  to  $57^{\circ}$ . A variety of environmental conditions were encountered from clear line-of-sight to heavy shadowing. The received pilot signal power on the forward link (hub-to-van) during a clear condition is shown in Figure 7. The constant overall signal level resembles an AWGN channel. The Gaussian channel is channel present under stationary conditions or in the absence of multipath. In contrast, a lightly shadowed case is shown in Figure 8. Here, considerably more signal variation is seen. The probability density functions derived from the experimental data for these two environments are shown in Figure 9.

The clear channel density function was fitted with an analytically-derived Rician density. This is shown also in Figure 9. The K-factor (ratio of direct to scattered power in a multipath environment) is 16.5 dB. It should be noted that K may have actually been higher; however, the noise present on the pilot (approximately 42 dB.Hz C/N<sub>0</sub>), and the noise inherent in the data acquisition system limited the values of observable K. This high value of K (16.5 dB) shows that the distribution approaches the Gaussian. This reiterates the observation that the clear mobile channel, with a medium gain vehicle antenna, and at a sufficiently high elevation angle, is approximately an AWGN link.

Both antennas tracking subsystems operated well and performed as expected. The modem and speech coder subsystems also performed well. Preliminary analyses have indicated that the return link performance under generally clear conditions was 8.5 to 9.0 dB for a BER of about  $10^{-3}$ . The forward link required 8.5 to 9.5 dB E<sub>b</sub>/N<sub>0</sub> for the same performance. These results show approximately a 0.2 to 1.2 dB degradation relative to hardware performance in the lab.

Overall, and in a qualitative manner as well, the MSAT-X system demonstrated good and robust performance. Good speech quality was observed for the many voice test tapes used. The robustness of the system was shown by a nearly continuous two hour voice link, during which synchronization was maintained over the range of environmental conditions. Short blockages resulted only in short bursts of codec induced silence or, seldom, garbled speech.

Detailed data analysis of the experiment is on-going and more complete results will be published in forthcoming articles.

#### **Multipath Rejection Measurement Experiment (MRMEx)**

MRMEx is scheduled for July/August 1990. It will evaluate the ability of directive antennas to discriminate against multipath signals. This will lead to an estimate of the attendant system performance improvement. The mobile terminal will be mounted on the MSAT-X van and will receive signals from a satellite while the van is driven on various roads. A variety of propagation environments will be encountered. The signal will be received simultaneously through both an omni and a directive antenna. Several tracking, directive antennas will be tested. The received in-phase and quadrature signals will be recorded for both antennas simultaneously. The data will be analyzed to determine the propagation characteristics observed with each antenna type.

#### **4. CONCLUSIONS**

Both the quantitative and qualitative results of the two latest field experiments show the viability and applicability of the MSAT-X architecture and technology. Technological risks associated with the implementation of a first generation MSS have been shown to be minimal. Commercialization of the speech codec and modem technology is already underway. Commercial implementation of mechanically steered antennas is feasible today. Some additional development work, however, remains in the area of electronically steered antennas. The greatest challenge will be in reducing the cost of the phased arrays. Through the combination of research, development and field testing, MSAT-X technology has now been shown to be a viable MSS option that can be adopted by U.S. industry.

## ACKNOWLEDGMENT

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Table 1. Summary of Pilot Field Experiments

| <u>Experiment</u> | <u>Date</u> | <u>Purpose</u>                                      |
|-------------------|-------------|---|
| Tower 1           | Winter '87  | Antenna acquisition & tracking                      |
| Satellite 1a      | Summer '87  | Antenna acquisition & tracking                      |
| Tower 2           | Fall ' 87   | Antenna acquisition & tracking & half duplex data   |
| Tower 3           | Summer' 88  | End-to-end data & voice performance & demonstration |
| MSAT-X/FAA        | Winter' 89  | Fixed ground and aeronautical-mobile end-to-end     |
| MSAT-X/AUSSAT     | Summer' 89  | Full scale land-mobile                              |
| MRMEx             | Summer' 90  | Antenna multipath rejection                         |

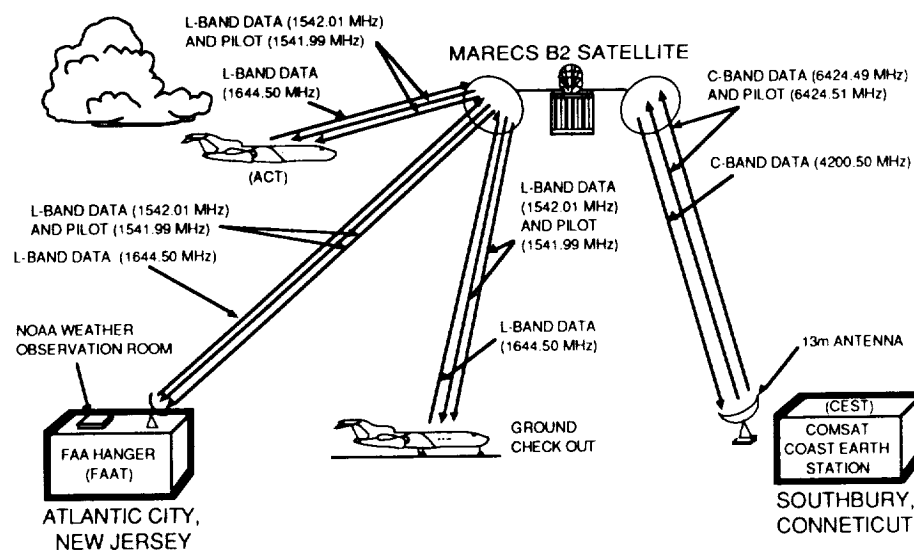


Figure 1. MSAT-X/FAA/COMSAT/INMARSAT Experiment

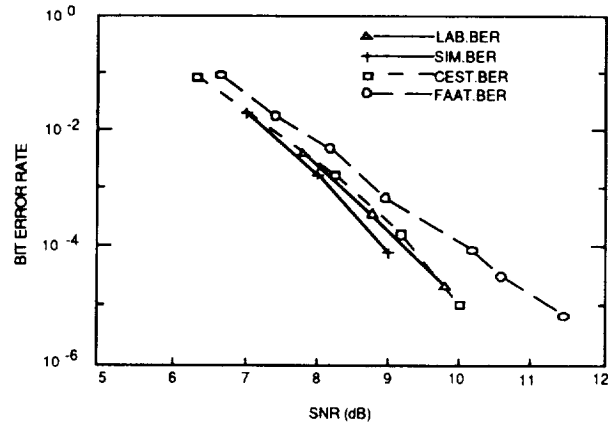


Figure 2. Ground Based Forward and Return Link BER Measurements  
(SNR of 8 dB =  $C/N_0$  of 44.8 dB.Hz)

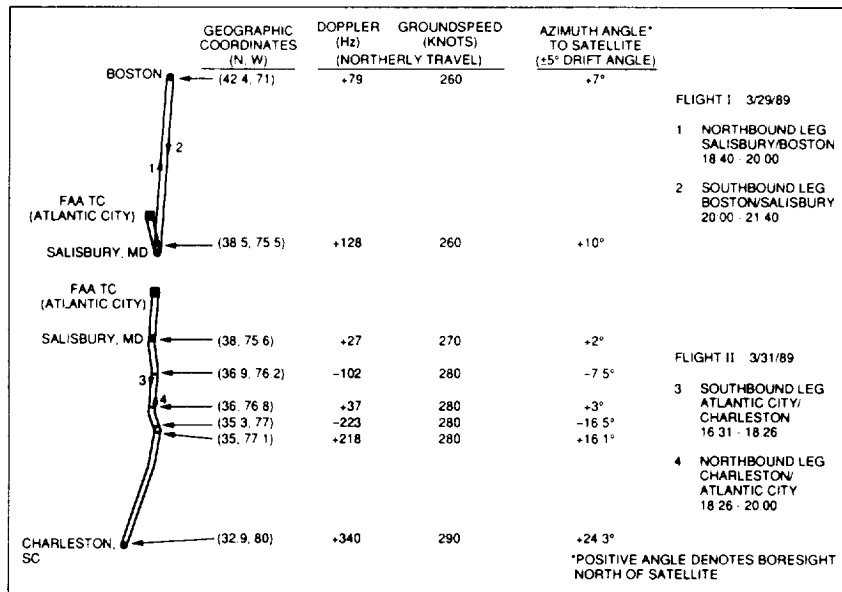


Figure 3. Flight Paths

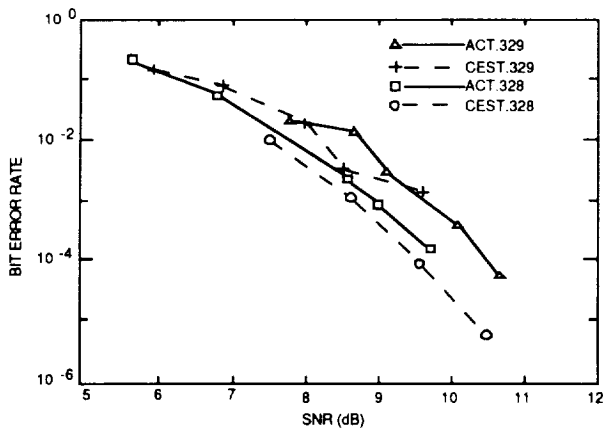


Figure 4. Flight #1 BER Performance

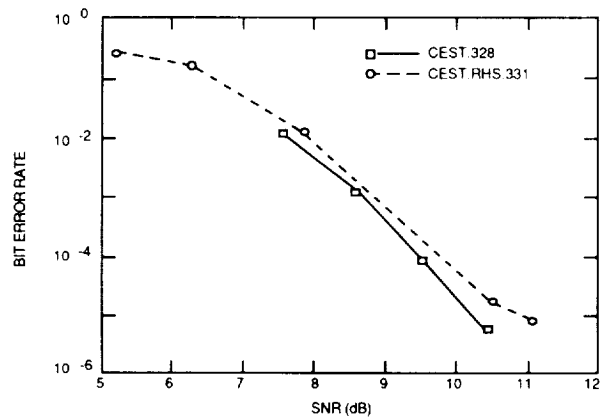


Figure 5. Return Link BER Performance from Flight #2

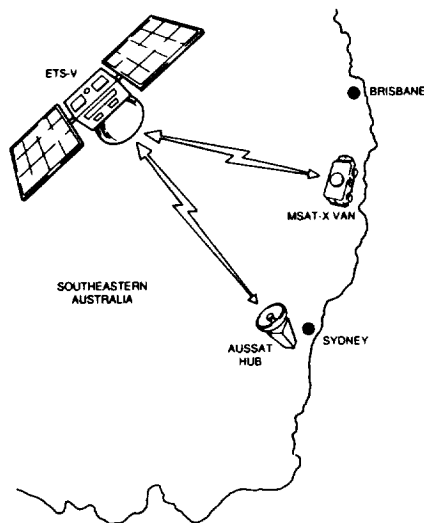


Figure 6. MSAT-X/AUSSAT Experiment Configuration

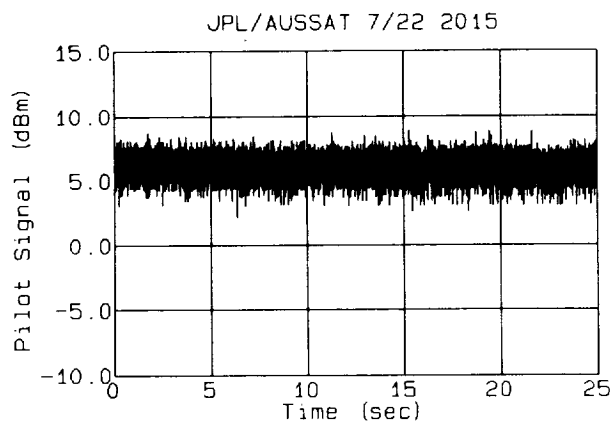


Figure 7. Received Pilot on Clear Channel

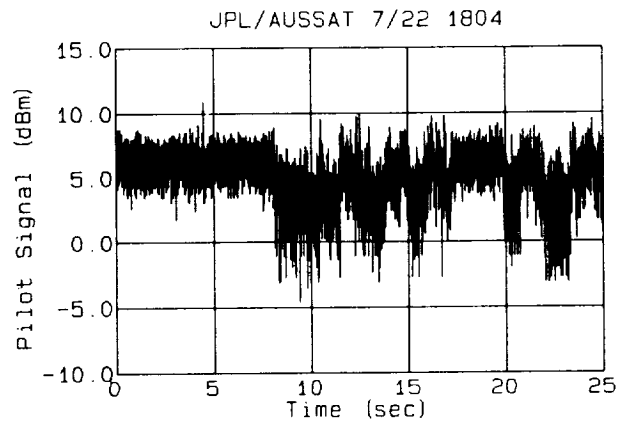


Figure 8. Received Pilot on Channel with Light to Moderate Shadowing

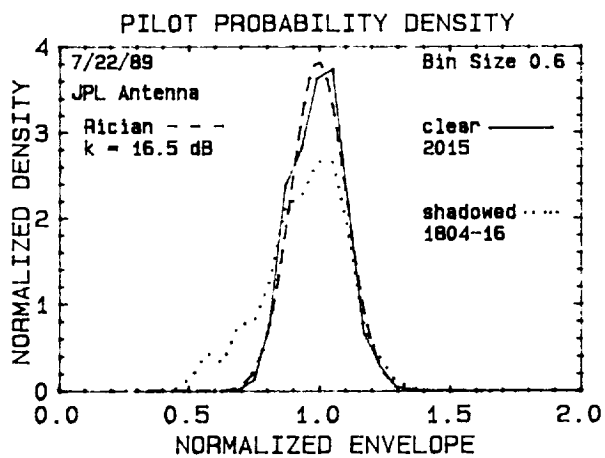


Figure 9. Probability Density Functions for Envelope of Received Pilot